NONLINEAR POLARIZATION AMPLIFIERS IN NONZERO DISPERSION SHIFTED FIBER

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. Application No. 09/766,489, titled "Nonlinear Polarization Amplifiers in Nonzero Dispersion Shifted Fiber," filed January 19, 2001, which is a continuation-in-part of and claims the benefit of priority from the U.S. Application titled "Low-Noise Distributed Raman Amplifier Using Bi-Directional Pumping Using Multiple Raman Orders," filed January 12, 2001, and claims the benefit of priority from U.S. Application No. 09/565,776, filed May 5, 2000, which claims the benefit of 09/046,900 filed March 24, 1998, which applications are fully incorporated herein by reference.

TECHNICAL FIELD OF THE INVENTION:

The present invention relates generally to nonlinear polarization amplifiers, and more particularly to nonlinear polarization amplifiers used to amplify signals propagating in non-zero dispersion shifted optical fibers.

BACKGROUND OF THE INVENTION

Because of the increase in data intensive applications, the demand for bandwidth in communications has been growing tremendously. In response, the installed capacity of telecommunication systems has been increasing by an order of magnitude every three to four years since the mid 1970s. Much of this capacity increase has been supplied by optical fibers that provide a four-order-of-magnitude bandwidth enhancement over twisted-pair copper wires.

To exploit the bandwidth of optical fibers, two key technologies have been developed and used in the telecommunication industry: optical amplifiers and wavelength-division multiplexing (WDM). Optical amplifiers boost the signal strength and compensate for inherent fiber loss and other splitting and insertion losses. WDM enables different wavelengths of light to carry different signals parallel over the same optical fiber. Although WDM is critical in that it allows utilization of a major fraction of the fiber bandwidth, it would not be cost-effective without optical amplifiers. In particular, a broadband optical amplifier that permits simultaneous amplification of many WDM channels is a key enabler for utilizing the full fiber bandwidth.

Silica-based optical fiber has its lowest loss window around 1550nm with approximately 25THz of bandwidth between 1430 and 1620nm. For example, Figure 1 illustrates the loss profile of a 50km optical fiber. In this wavelength region, erbium-doped fiber amplifiers (EDFAs) are widely used. However, as indicated in Figure 2, the absorption band of a EDFA nearly overlaps its the emission band. For wavelengths shorter than about 1525nm, erbium-atoms in typical glasses will absorb more than amplify. To broaden the gain spectra of EDFAs, various dopings have been added. For example, as shown in Figure 3a, codoping of the silica core with aluminum or phosphorus broadens the emission spectrum considerably. Nevertheless, as depicted in Figure 3b, the absorption peak for the various glasses is still around 1530nm.

Hence, broadening the bandwidth of EDFAs to accommodate a larger number of WDM channels has become a subject of intense research. As an example of the state-of-the-art, a two-band architecture for an ultra-wideband EDFA with a record optical bandwidth of 80 nm has been demonstrated. To obtain a low noise figure and

high output power, the two bands share a common first gain section and have distinct second gain sections. The 80nm bandwidth comes from one amplifier (so-called conventional band or C-band) from 1525.6 to 1562.5nm and another amplifier (so-called long band or L-band) from 1569.4 to 1612.8nm. As other examples, a 54nm gain bandwidth achieved with two EDFAs in a parallel configuration, i.e., one optimized for 1530-1560nm and the other optimized for 1576-1600nm, and a 52nm EDFA that used two-stage EDFAs with an intermediate equalizer, have been demonstrated.

These recent developments illustrate several points in the search for broader bandwidth amplifiers for the low-loss window in optical fibers. First, bandwidth in excess of 40-50nm require the use of parallel combination of amplifiers even with EDFAs. Second, the 80nm bandwidth may be very close to the theoretical maximum. The short wavelength side at about 1525nm is limited by the inherent absorption in erbium, and long wavelength side is limited by bend-induced losses in standard fibers at above 1620nm. Therefore, even with these recent advances, half of the bandwidth of the low-loss window, i.e., 1430-1530nm, remains without an optical amplifier.

There is a need for nonlinear polarization amplifiers that provide a low noise figure amplification for operation near the zero dispersion wavelength of fibers. There is a further need for a broadband fiber transmission system that includes nonlinear polarization amplifiers which provide low noise amplification near the zero dispersion wavelength of fibers.

SUMMARY OF THE INVENTION

Accordingly, an object of the present invention is to provide nonlinear polarization amplifiers.

Another object of the present invention is to provide a broadband fiber transmission system with at least one nonlinear polarization amplifier.

Yet another object of the present invention is to provide a broadband fiber transmission system with reduced fiber non-linear impairments.

A further another object of the present invention is to provide a broadband fiber transmission system that operates over the full low loss window of available and optical fibers.

Another object of the present invention is to provide a broadband fiber transmission system that uses distributed Raman amplification to lower signal power requirements.

These and other objects of the present invention are achieved in a broadband fiber transmission system. The broadband fiber transmission system includes a transmission line with at least one zero dispersion wavelength λ_o and transmits an optical signal of λ. The transmission line includes a distributed Raman amplifier that amplifies the optical signal through Raman gain. One or more semiconductor lasers are included and operated at wavelengths λ_p for generating a pump light to pump the Raman amplifier. λ is close to λ_0 and λ_0 is less than 1540 nm or greater than 1560 nm.

In another embodiment of the present invention, a broadband fiber transmission system is provided. A transmission line includes at least one zero dispersion wavelength λ_o and transmits an optical signal of λ. The transmission line includes a distributed Raman amplifier and a discrete optical amplifier that amplify the optical signal of λ. One or more pump sources are included and operated at wavelengths λ_p for generating a pump light to pump the amplifiers. λ is close to λ_0 and λ_0 is less than 1540 nm or greater than 1560 nm.

In another embodiment of the present invention, a method of broadband amplification provides a broadband fiber transmission system with a transmission line having at least one zero dispersion wavelength λ_o. The transmission line includes a Raman gain medium that amplifies an optical signal through Raman gain. An optical

signal of λ is transmitted. The Raman amplifier is pumped with pump light λ_p. λ is close to λ_0 and λ_0 is less than 1540 nm or greater than 1560 nm.

In another embodiment of the present invention, a method of broadband amplification provides a broadband fiber transmission system with a transmission line having at least one zero dispersion wavelength λ_o. The transmission line includes a distributed Raman amplifier and a discrete optical amplifier that amplify an optical signal of λ. An optical signal of λ is transmitted. The Raman amplifier and discrete optical amplifiers are pumped with pump light λ_p. λ is close to λ_0 and λ_0 is less than 1540 nm or greater than 1560 nm.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a plot of loss verses wavelength for 50km fiber and the gain band of a typical EDFA.

Figure 2 is a graphical illustration of absorption and gain spectra of an EDFA.

Figure 3a is a graphical illustration of emission spectra of four EDFAs with different core compositions.

Figure 3b is a graphical illustration of absorption cross-section of erbium-doped glass of different compositions.

Figure 4 is a graphical illustration of a measured Raman-gain spectrum for fused silica at a pump wavelength of 1000nm.

Figure 5 is a graphical illustration that plots power gain coefficient 2g versus phase vector mismatch Δk for parametric amplification.

Figure 6 is a schematic diagram of one embodiment of a nonlinear polarization amplifier of the present invention.

Figure 7 is a graphical illustration of spectral broadening and gain expected from parametric amplification for a pump power of 1W and different separations between the pump and zero-dispersion wavelength.

Figure 8 is a graphical illustration of spectral broadening and gain expected from parametric amplification for a pump and zero-dispersion wavelength separation of 1nm and for varying pump powers.

Figure 9 is a schematic diagram of an embodiment of a broadband fiber transmission system of the present invention using an open-loop configuration.

Figure 10 is a schematic illustration of a broadband fiber transmission system of the present invention using a Sagnac Raman cavity that is pumped at 1240nm.

Figure 11 is a schematic illustration of an embodiment of a broadband fiber transmission system of the present invention using a Sagnac Raman cavity that is pumped at 1117nm.

Figure 12 is a schematic illustration of an embodiment of a broadband fiber transmission system of the present invention with two stages of nonlinear polarization amplifiers.

Figure 13 is a schematic illustration of an embodiment of a broadband fiber transmission system of the present invention that is a combination of an EDFA and a nonlinear polarization amplifier.

Figure 14 is a schematic diagram of one embodiment of a dual stage amplifier.

Figure 15 is a graph of gain versus wavelength for an S band dual stage amplifier, such as for the embodiment of Figure 14.

Figure 16 is a graph of noise figure versus wavelength for an S band dual stage amplifier, such as for the embodiment of Figure 14.

Figure 17 is a block chart of various embodiments of uses of amplifiers.

DETAILED DESCRIPTION OF THE INVENTION

Some embodiments provide a structure for exploiting almost the full 25THz of bandwidth available in the low-loss window of optical fibers from 1430nm to 1620nm. The broadband NLPA amplifier of some embodiments combines Raman amplification with either PA or 4WM to achieve bandwidth performance improvements that neither technology by itself has heretofore been able to deliver.

The broadband NLPA of other embodiments comprise an input port for inputting an optical signal having a wavelength λ, a distributed gain medium for receiving the optical signal and amplifying and spectrally broadening the same therein through nonlinear polarization, a pump source operated at wavelength λ_p for generating a pumping light to pump the distributed gain medium, and an output port for outputting the amplified and spectrally broadened optical signal. The distributed gain medium can have zero-dispersion at wavelength λ_0 such that $\lambda \geq \lambda_0 \geq \lambda_p$. The pumping light can cascade through the distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_r at a close proximity to the zero-dispersion wavelength λ_0 to phase match four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$).

A first embodiment of the NLPA uses open-loop amplification with an optical fiber gain medium. A pump source operated at 1240nm can be used. The pump may be retro-reflected to increase the conversion efficiency. A second embodiment of the NLPA can use a Sagnac Raman cavity that is pumped at 1240nm. Feedback in the Sagnac Raman cavity can reduce the required pump power, and the broadband cavity design supports much of the generated bandwidth. Another embodiment of the NLPA can use a Sagnac Raman cavity pumped at 1117nm for a very broadband operation.

Other embodiments relate to a parallel optical amplification apparatus having a combination of optical amplifiers. In one embodiment, the parallel optical amplification apparatus comprises two parallel stages of NLPAs with one NLPA optimized for 1430 to 1480nm and the other for 1480 to 1530nm. In another embodiment, the full 25THz of the low-loss window in optical fibers can be exploited by a parallel combination of a Raman amplifier and a rare earth doped amplifier. In one embodiment, an NLPA can cover the low-loss window of approximately 1430nm

to 1530nm, and an EDFA can cover the low-loss window of approximately 1530nm to 1620nm.

Stimulated Raman scattering effect, PA and 4WM can be result of third-order nonlinearities that occur when a dielectric material such as an optical fiber is exposed to intense light. The third-order nonlinear effect can be proportional to the instantaneous light intensity.

Stimulated Raman scattering can be an important nonlinear process that turns optical fibers into amplifiers and tunable lasers. Raman gain can result from the interaction of intense light with optical phonons in silica fibers, and Raman effect leads to a transfer of energy from one optical beam (the pump) to another optical beam (the signal). The signal can be downshifted in frequency (or upshifted in wavelength) by an amount determined by vibrational modes of silica fibers. The Raman gain coefficient g_r for the silica fibers is shown in Figure 4. Notably, the Raman gain g_r can extend over a large frequency range (up to 40 THz) with a broad peak centered at 13.2 THz (corresponding to a wavelength of 440 cm^{-1}). This behavior over the large frequency range can be due to the amorphous nature of the silica glass and enable the Raman effect to be used in broadband amplifiers. The Raman gain can depend on the composition of the fiber core and can vary with different dopant concentrations.

Raman amplification has some attractive features. First, Raman gain can upgrade existing fiber optic links because it is based on the interaction of pump light with optical phonons in the existing fibers. Second, in some embodiments there is no excessive loss in the absence of pump power - an important consideration for system reliability.

Raman cascading is the mechanism by which optical energy at the pump wavelength is transferred, through a series of nonlinear polarizations, to an optical signal at a longer wavelength. Each nonlinear polarization of the dielectric can produce a molecular vibrational state corresponding to a wavelength that is offset from the wavelength of the light that produced the stimulation. The nonlinear polarization effect can be distributed throughout the dielectric, resulting in a cascading series of wavelength shifts as energy at one wavelength excites a vibrational mode that produces light at a longer wavelength. This process can cascade through

numerous orders. Because the Raman gain profile can have a peak centered at 13.2THz in silica fibers, one Raman order can be arranged to be separated from the previous order by 13.2THz.

Cascading makes stimulated Raman scattering amplifiers very desirable. Raman amplification can be used to amplify multiple wavelengths (as in wavelength division multiplexing) or short optical pulses because the gain spectrum can be very broad (a bandwidth of greater than 5THz around the peak at 13.2THz). Cascading can enable Raman amplification over a wide range of different wavelengths. By varying the pump wavelength or by using cascaded orders of Raman gain, the gain can be provided over the entire telecommunications window between 1300nm and 1600nm.

Parametric amplification and 4 wave mixing (PA/4WM) involve two pump (P) photons that create Stokes (S) and anti-Stokes (A) photons. Both PA/4WM and Raman amplification arise from the third order susceptibility $\chi^{(3)}$ in optical fibers. More specifically, the real part of $\chi^{(3)}$, the so-called nonlinear index of refraction n_2, is responsible for PA/4WM, while the imaginary part of $\chi^{(3)}$ associated with molecular vibrations corresponds to the Raman gain effect. In silica fibers of some embodiments, about 4/5ths of the n_2 is an electronic, instantaneous nonlinearity caused by ultraviolet resonances, while about 1/5th of n_2 arises from Raman-active vibrations, e.g., optical phonons. The imaginary part of this latter contribution corresponds to the Raman gain spectrum of Figure 4.

Whereas Raman amplification is attractive for providing optical gain, PA/4WM can offer an efficient method to broaden the bandwidth of the optical gain. PA/4WM can have a much smaller frequency separation between pump and signal than Raman amplification, and the frequency difference may depend on the pump intensity. As in Raman amplification, one advantage of PA/4WM gain is that it can be present in every fiber. However, unlike the Raman effect, both PA and 4WM can require phase-matching. 4WM can be inefficient in long fibers due to the requirement for phase-matching. However, PA can act as self-phase-matched because the nonlinear index of refraction is used to phase match the pump and sidebands. This can be true in embodiments operating near the zero-dispersion wavelength in fibers. When 4WM and PA occur near the zero-dispersion wavelength of a single-mode fiber, phase-matching can become automatic in the fiber. In 4WM, sidebands can be

generated without gain when the pump wavelength falls in the normal dispersion regime (where the pumping wavelength is shorter than the zero-dispersion wavelength). PA is 4-photon amplification in which the nonlinear index of refraction is used to phase match the pump and sidebands. For PA the pump wavelength can lie in the anomalous group velocity regime (i.e., where the pumping wavelength is longer than the zero-dispersion wavelength) and proper phase matching can require that pump and signal be co-propagating in some embodiments.

To illustrate the PA/4WM gain, the gain coefficient can be derived as:

$$g = \sqrt{(\gamma P)^2 - \left[\left(\frac{\Delta\kappa}{2}\right) + \gamma P\right]^2} \qquad \mathbf{1}$$

The first term under the square root sign corresponds to the third order nonlinearity that couples the pump photons to the sidebands. The second term corresponds to the phase mismatch between the waves and it consists of two parts: one due to the wave-vector mismatch at the different wavelengths and the other due to the increase in nonlinear index induced by the pump. The nonlinearity parameter can be defined as

$$\gamma = \frac{\omega}{c}\frac{n_2}{A_{eff}} = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}} \qquad \mathbf{2}$$

Some embodiments operate near the zero-dispersion wavelength λ_0, and the propagation constant can be expanded as:

$$\Delta\kappa = -\frac{\lambda^2}{2\pi c}\left[\left.\frac{dD}{d\lambda}\right|_{\lambda_0}(\lambda_p - \lambda_0)\right]\Omega^2 \qquad \mathbf{3}$$

where

$$\Omega = \omega_p - \omega_s = \omega_a - \omega_p. \qquad \mathbf{4}$$

The pump wavelength can falls in the normal dispersion regime for some embodiments, and $D < 0$, $\partial D/\partial\lambda > 0$, $(\lambda_p - \lambda_0) < 0$, so that $\Delta k > 0$. In this case, g can be imaginary, and there may be no gain during the sideband generation process. This can correspond to the case of 4WM. Some embodiments operate in the anomalous group velocity dispersion regime, and $D > 0$, $\partial D/\partial\lambda > 0$, $(\lambda_p - \lambda_0) > 0$, so that $\Delta k < 0$. This can be the regime of PA, and the nonlinearity helps to reduce the phase mismatch (i.e., the two parts in the second term in Equation (1) are of opposite sign). There can be gain for PA, and the gain can be tunable with the pump power. For example, the power gain coefficient 2g is plotted schematically in Figure 5 for operation in the anomalous group velocity regime. The peak gain ($g_{peak}=\gamma P$) can occur at $\Delta k_{peak}=-2\gamma P$. The range over which the gain exists can be given by $0 > \Delta k > -4\gamma P$ in some embodiments. Thus, the peak gain can be proportional to the pump power, and the Δk range can be determined by the pump power.

Consequently, from Equation (2) the bandwidth can be increased by increasing the pump power, increasing the nonlinear coefficient n_2 or decreasing the effective area A_{eff}. In other embodiments, for a given required frequency range over which gain is required, the pump requirements can be reduced by increasing the effective nonlinearity (n_2/A_{eff}).

Several embodiments lead to broadband gain for cascaded Raman amplification by arranging at least one intermediate Raman cascade order at close proximity to the zero-dispersion wavelength λ_0 (e.g., within ±5nm of λ_0 for some embodiments; within ±2nm for other embodiments). Either 4WM (if $\lambda_r < \lambda_0$) or PA (if $\lambda_r > \lambda_0$) can lead to spectral broadening of that particular Raman order. In subsequent Raman orders the bandwidth can grow even further. In other embodiments, the cascade Raman wavelength λ_r lies to the long wavelength side of λ_0 (i.e., in the anomalous dispersion regime), so that parametric amplification can occur.

An embodiment of the broadband NLPA is illustrated in Figure 6. Starting from the pump wavelength λ_p, cascaded Raman amplification can be used in the first few stages. The pump can be more than one Raman shift or 13.2THz away from the zero-dispersion wavelength. To keep higher efficiency in these initial steps, some embodiments can use a narrow band cavity design, such as designs based on gratings or wavelength selective couplers.

Some embodiments broaden the gain bandwidth by positioning one of the intermediate Raman cascade orders at a close proximity to the zero-dispersion wavelength λ_0. By operating close to λ_0, it can almost automatically phase-match either 4WM or PA. In the subsequent cascaded Raman orders, the gain bandwidth may continue to broaden. This occurs because the effective gain bandwidth of Raman is the convolution of the bandwidth of the pump (in this case, the previous Raman cascade order) with the Raman gain curve. In some embodiments with Raman amplification, the gain spectrum follows the pump spectrum. As the pump wavelength changes, the Raman gain can change as well, separated by the distance of optical phonon energy which in silica fibers is an approximately 13.2THz down-shift in frequency.

If the fiber is conventional so-called standard fiber, then zero-dispersion wavelength λ_0 can be about 1310nm. For dispersion-shifted fiber, the zero-dispersion wavelength λ_0 can shift to longer wavelengths by adding waveguide dispersion. In other embodiments, a dispersion-flattened fiber can be used for low dispersion values over one or more of the Raman cascade orders. In some embodiments with dispersion-flattened fiber, the dispersion slope can be small, so the gain bandwidth can be even larger (c.f. Equations (1) and (3)).

The Raman gain spectrum can follow the pump spectrum, such as when there is nothing in the Raman cavity to restrict the bandwidth of the subsequent orders. For these higher cascade order Raman laser schemes, some embodiments use gratings or wavelength selective couplers. Other embodiments with the broadband cavity design of the Sagnac Raman amplifier and laser can have increased bandwidth with a tailored pump spectrum. A single-pass fiber design can constitute the broadest bandwidth design. A broadband cavity such as the Sagnac Raman cavity can have the feedback used to lower the threshold and the required pump power. Broadening the bandwidth can lead to a drop in efficiency, so the pump powers can be higher for the broadband cavity designs.

Cascaded Raman amplification can reach the 1430-1530nm range of the low-loss window. Pumping can occur with a commercially available cladding-pumped fiber laser, which operates around 1060 to 1140nm. The various Raman orders, each separated by 13.2Thz from the previous order, are set forth in Table 1.

Table 1. Various Raman orders when pumping between 1060 and 1140nm (separation of 13.2THz between orders)

Wavelength (nm)	$\Delta\lambda$	Wavelength (nm)	$\Delta\lambda$
1060.00	51.86	1110.00	57.00
1111.86	57.19	1167.00	63.17
1169.05	63.39	1230.16	70.40
1232.44	70.66	1300.56	78.94
1303.11	79.26	1379.50	89.14
1382.37	89.53	1468.64	101.46
1471.90	101.93	1570.10	116.52
1573.82	117.09	1686.62	135.20
Wavelength (nm)	$\Delta\lambda$	Wavelength (nm)	$\Delta\lambda$
1070.00	52.86	1117.00	57.74
1122.86	58.36	1174.74	64.03
1181.22	64.76	1238.77	71.41
1245.98	72.27	1310.18	80.15
1318.25	81.17	1390.33	90.59
1399.42	91.82	1480.92	103.22
1491.25	104.72	1584.15	118.69
1595.97	120.54	1702.84	137.92
Wavelength (nm)	$\Delta\lambda$	Wavelength (nm)	$\Delta\lambda$
1080.00	53.88	1120.00	58.05
1133.88	59.54	1178.05	64.40
1193.42	66.14	1242.46	71.85
1259.56	73.90	1314.31	80.67
1333.47	83.11	1394.98	91.22
1416.58	94.16	1486.20	103.99
1510.74	107.57	1590.19	119.63
1618.32	124.07	1709.82	139.10
Wavelength (nm)	$\Delta\lambda$	Wavelength (nm)	$\Delta\lambda$
1090.00	54.91	1130.00	59.12
1144.91	60.74	1189.12	65.65
1205.65	67.54	1254.77	73.32
1273.19	75.56	1328.10	82.43
1348.74	85.09	1410.53	93.33
1433.83	96.55	1503.86	106.56
1530.38	110.49	1610.42	122.81
1640.87	127.69	1733.24	143.09
Wavelength (nm)	$\Delta\lambda$	Wavelength (nm)	$\Delta\lambda$
1100.00	55.95	1140.00	60.20

1155.95	61.94	1200.20	66.92
1217.89	68.96	1267.12	74.82
1286.85	77.24	1341.93	84.21
1364.09	87.10	1426.14	95.48
1451.19	98.98	1521.62	109.18
1550.17	113.47	1630.81	126.07
1663.64	131.40	1756.87	147.19

To obtain gain between 1430nm and 1520nm, the pump can be operated between 1090nm and 1140nm, and five cascaded Raman orders can be used to reach the desired wavelength. To make use of the broadening from PA or 4WM, a pumping scheme can be selected in the middle of this range, i.e., starting with a pump wavelength of 1117nm. Then, the various Raman orders land at approximately 1175nm, 1240nm, 1310nm, 1390nm and finally 1480nm. In particular, the third Raman frequency (1310nm) passes through the zero-dispersion point of a standard fiber, and the next order (1390nm) can be close if the fiber is dispersion shifted. A broadband gain can be expected for wavelengths in the 1430-1530nm range centered around 1480nm by using a fiber with a standard dispersion and a pump wavelength of 1117nm, 1175nm or 1240nm.

Broadening can be expected from PA. A standard fiber can be used and the pump wavelength can start at 1117nm. The calculations use Equations (1-4) with the following typical parameters for high-Raman cross-section fiber in some embodiments: λ_0 = 1310nm, $\gamma = 9.9\mathrm{W}^{-1}\mathrm{km}^{-1}$, and a dispersion slope of 0.05ps/nm-km. In Figure 7, the gain coefficient for PA is plotted versus wavelength at a pump power of 1W and wavelength separations (λ_r-λ_0) of 0.5, 1, 2 and 5nm. For a wavelength separation of 2nm, the PA peak gain occurs at ±10nm, so the spectral broadening is over 20nm. The closer the pump wavelength approaches the zero-dispersion wavelength, the wider the gain bandwidth can be. In addition, Figure 8 plots the gain versus wavelength for a separation of (λ_r-λ_0)=1nm and pump powers of 0.7, 1, 2, and 3W. The peak gain can increase directly proportionally to the pump power, while the bandwidth can increase as the square root of pump power.

Figure 9 shows a first embodiment that uses an open-loop design to produce an amplified broadband signal for a range of wavelengths between 1430nm and 1530nm. The open-loop design is a nonlinear polarization amplifier, and may have a

high pump power requirement. In the NLPA amplifier 20 as illustrated in Figure 9, an optical signal having a wavelength between 1430nm and 1530nm is input from an input port 25 to an optical fiber 30. The optical fiber 30 is pumped by a pumping light generated by a pumping laser 35 operated at a wavelength of about 1240nm. The optical signal is amplified and spectrally broadened in the fiber by nonlinear polarization, and output through an output port 40. The configuration is so arranged that the optical signal can have a wavelength greater than the zero-dispersion wavelength of the fiber, which in turn is greater than the pumping wavelength of 1240nm.

In this open-loop configuration, the fiber can have a cut-off wavelength below 1240nm to be single-mode (spatial) over all wavelengths of the Raman cascade. Three choices of the fiber embodiments can be used in some embodiments. First, a standard dispersion fiber with a zero-dispersion wavelength at about 1310nm. Second, two fibers spliced together with one fiber having a zero-dispersion wavelength at about 1310nm (first cascade) and the other at 1390nm (second cascade). Third, a dispersion-flattened fiber with low-dispersion at least between 1310nm and 1390nm. The reduced dispersion slope of such a dispersion-flattened fiber increases significantly the bandwidth for PA or 4WM.

Exemplary 1240nm pump lasers include: (a) an 1117nm cladding-pumped fiber laser followed by a coupler-based or grating-based Raman oscillator cavity (with gratings for 1117nm, 1175nm and 1240nm); (b) an optically-pumped semiconductor laser; or (c) a chromium-doped forsterite laser. At one end of the fiber, a 1240nm retro-reflector 45 can be placed to increase pumping conversion efficiency. The retro-reflector can be a dichroic mirror or a 1240nm grating. The input and output ports can be WDM couplers, and isolators can be used at the input and output ports to prevent lasing due to spurious feedback. A counter-propagating geometry can average out noise fluctuations in this open-loop configuration. A co-propagating geometry can be used.

To reduce the pump power requirements, a broadband cavity such as the Sagnac Raman cavity can be used in some embodiments. Figure 10 illustrates an embodiment of the NLPA that uses a Sagnac Raman cavity design with a 1240nm pump. Referring to Figure 10, the Sagnac Raman cavity of the NLPA 60 can be

formed by a broadband mirror 70 and a loop mirror comprising a Raman gain fiber 65 and an optical coupler 90 connected thereto. An optical signal can have a wavelength between 1430nm to 1530nm input through an input port 75 to the Raman gain fiber 65. A pumping laser 80 can operate at a wavelength 1240nm and generate a pumping light that pumps the fiber 65 through a coupler 85. The optical signal can be amplified and spectrally broadened in the fiber by nonlinear polarization, and output through an output port 95. The configuration can be arranged so that the optical signal has a wavelength greater than the zero-dispersion wavelength of the fiber, which in turn can be greater than the pumping wavelength of 1240nm.

The Raman gain fiber can have the same characteristics as described above for the open-loop design. Similarly, the pumping lasers used in the first embodiment can be used in this second embodiment. The broadband NLPA may further include a polarization controller 100 in the Sagnac Raman cavity for controlling polarization state. In other embodiments, if the fiber is polarization maintained, the polarization controller can be unnecessary. The optical coupler 90 is nominally 50:50 at least for the optical signal having a wavelength between about 1240nm and 1430nm. The coupler 85 can be a WDM coupler that transmits at least at a wavelength between about 1300nm and 1430nm. The input port and output port each comprises a WDM coupler which can transmit at least at a wavelength between about 1240nm and 1425nm. One embodiment of the Sagnac Raman cavity has a passive noise dampening property that leads to quieter cascading of various Raman orders.

In various embodiments, a Sagnac Raman cavity can be used for all five Raman cascade orders between 1117nm and the low-loss window. Figure 11 illustrates a third embodiment of a five-order Sagnac Raman amplifier for NLPA operation. A cladding-pumped fiber laser operating around 1117nm can be used as a pumping laser 120. Different fiber combinations embodiment can be used. The fibers can have a cut-off wavelength below 1117nm to accommodate single-mode operation for the pump. An optical coupler 130 can be nominally 50:50 at least for the optical signal having the wavelength between about 1117nm and 1430nm. A coupler 125 can be a WDM coupler that transmits at least at wavelengths between about 1165nm and 1430nm. Moreover, the input and output ports each comprises a WDM coupler which can transmit at least at wavelengths between about 1117nm and 1425nm. Although

the wavelength range of the various components increases, this configuration can lead to an even broader gain band since the pump bandwidth is allowed to increase even during the first two cascades between 1117nm and 1240nm for some embodiments. Also, the noise dampening property of the Sagnac cavity can be used over all five Raman orders for some embodiments.

Some embodiments include an NLPA. An optical signal having a wavelength λ is input through an input port into a distributed gain medium having zero-dispersion at a wavelength λ_0, such as an optical fiber, which can be pumped by a pumping light from a pump source operated at a wavelength λ_p, wherein $\lambda \geq \lambda_0 \geq \lambda_p$. The pumping light can cascade through the distributed gain medium a plurality of Raman orders including an intermediate order having a wavelength λ_r at a close proximity to the zero-dispersion wavelength λ_0 to phase match four-wave mixing (if $\lambda_r < \lambda_0$) or parametric amplification (if $\lambda_r > \lambda_0$). The amplified and spectrally broadened optical signal is output through an output port.

The above embodiments demonstrate that a single NLPA can accommodate the full bandwidth of the low-loss window. Moreover, the full bandwidth of the low-loss window may be reached by using a parallel optical amplification apparatus having a combination of two or more Raman amplifiers and rare earth doped amplifiers. In some embodiments, the NLPAs and EDFAs are used.

Figure 12 shows a first embodiment of the parallel optical amplification apparatus using a combination of two NLPAs for a range of wavelengths between 1430nm and 1530nm. Referring to Figure 12, a divider 170 divides an optical signal having a wavelength between 1430nm to 1530nm at a predetermined wavelength, such as 1480nm, into a first beam having a wavelength less than the predetermined wavelength and a second beam having a wavelength greater than the predetermined wavelength in some embodiments. The first beam is input into a first NLPA 180 for amplification and spectral broadening therein. The second beam is input into a second NLPA 190 for amplification and spectral broadening therein. Outputs from the first and second NLPAs can be combined by a combiner 200 to produce an amplified and spectrally broadened optical signal. The input port 170 and output port 200 can be preferably WDM couplers in some embodiments.

In other embodiments the first NLPA 180 can be optimized for 1430-1480nm and centered at 1455nm, while the second NLPA can be optimized for 1480-1530nm and centered at 1505nm. From Table 1, these two windows can be achieved in a five-order cascade by starting with a pump wavelength of about 1100nm for the short-wavelength side and a pump wavelength of about 1130nm for the long-wavelength side. For the short-wavelength side, the fiber can have a zero-dispersion around 1365nm, while for the long-wavelength side, the fiber zero-dispersion can be around 1328nm or 1410nm.

The narrower-bandwidth for each NLPA can lead to an increased efficiency for each amplifier in some embodiments. Furthermore, the components may be more easily manufactured, since the wavelength window is not as large. The multiple amplifiers in some embodiments may allow for gradual upgrades of systems, adding bandwidth to the EDFA window as needed.

A spectrum of 1430-1620nm in the low-loss window can be amplified and spectrally broadened by using a parallel optical amplification apparatus comprising Raman amplifiers and rare earth doped amplifiers. Figure 13 describes a second embodiment of the parallel optical amplification apparatus. The amplification apparatus comprises a broadband NLPA 240 and a EDFA 250. A divider 230 of the apparatus divides an optical signal having a wavelength between 1430nm and 1620nm at a predetermined wavelength, preferably at 1525nm, into a first beam having a wavelength less than the predetermined wavelength and a second beam having a wavelength greater than the predetermined wavelength in some embodiments. The broadband NLPA 240 receives the first beam and produces an amplified broadband first beam. The EDFA 250 receives the second beam and produces an amplified broadband second beam. A combiner 260 combines the amplified and spectrally broadened first and second beams to produce an amplified broadband optical signal. Other embodiments can have WDM couplers for the divider 230 and the combiner 260.

To use some embodiments with multi-wavelength WDM channels, at the output of the amplifier, gain can be equalized. This wavelength dependency or nonuniformity of the gain band can have little impact on single-channel transmission. However, it can render the amplifier unsuitable for multichannel operation through a

cascade of amplifiers. As channels at different wavelengths propagate through a chain of amplifiers, they can accumulate increasing discrepancies between them in terms of gain and signal-to-noise ratio. Using gain-flattening elements can significantly increase the usable bandwidth of a long chain of amplifiers. For example, the NLPA can be followed by a gain flattening element to provide gain equalization for different channels in some embodiments. Alternately, the gain flattening element could be introduced directly into the Sagnac interferometer loop in other embodiments, such as in Figs. 10 or 11.

Due to the high pump power requirements of Raman amplifiers, some embodiments include higher efficiency Raman amplifiers, where the efficiency can be defined as the ratio of signal output to pump input. In one embodiment, the efficiency can be improved to the point that laser diodes (LD's) can be used to directly pump the Raman amplifier. As an exemplary benchmark, for a dual stage amplifier made from dispersion-shifted fiber (DSF) with a gain of >15dB and an electrical noise figure of <6dB, a pump power of about 1W can be required from the Raman oscillator or pump laser. This power level can require the combined powers from about eight LD's in one embodiment. If the pump requirements could be dropped by a factor of four or so, the pump powers could be achieved with the combination of two LD's that are polarization multiplexed in another embodiment. In one embodiment, four LD's could be used to provide more than 0.5W of power, and the remaining improvement factor could be used to reduce the gain fiber lengths.

One embodiment improves the efficiency of Raman amplifiers by increasing the effective nonlinearity of the fiber used as the gain medium. The effective nonlinear coefficient for the fiber can be defined as

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}}$$

where n_2 is the nonlinear index of refraction and A_{eff} is the effective area of the fiber. The Raman gain coefficient can be directly proportional to γ. The Raman coefficient is the imaginary part of the nonlinear susceptibility while the index is proportional to the real part of the susceptibility, and the nonlinear index and Raman gain will be related by the so-called Kramers-Kronig relations. For a dispersion shifted fiber at 1550nm wavelength with an $n_2 = 2.6 \times 10^{-16}$ cm^2/W and an $A_{eff} = 50\Phi m^2$, the

nonlinear coefficient can be about $\gamma = 2\ W^{-1}km^{-1}$. If this value is raised to over $3\ W^{-1}km^{-1}$, then the pump power or fiber lengths can be reduced in proportion to the increase in nonlinear coefficient.

Beyond the constraint on the Raman gain coefficient, the dispersion in the amplifier can be restricted. To maintain a relatively low level of dispersion in the vicinity of the signal wavelengths, the zero dispersion wavelength λ_o can be in close proximity to the operating wavelength. For single-channel, high-bit-rate systems, one embodiment minimizes the dispersion by placing the signal wavelength within 10nm of the λ_o. For some embodiments of multi-wavelength WDM systems, where the channels can interact through four-wave mixing in the vicinity of λ_o, a dispersion-managed fiber can be used. A dispersion-managed fiber can have a locally high dispersion but a path-averaged value for dispersion close to zero by combining lengths of plus and minus values for the dispersion around the operating band. For the operating wavelength band, some segments of fiber can have λ_o at shorter wavelengths and some segments of fiber can have λ_o at longer wavelengths.

By proper design of the fiber, higher nonlinearity and lower dispersion can be achieved. For example, for operation in the S-band around 1520nm, high nonlinearity fibers have been produced. The fiber core can have a modified parabolic refractive index profile with a $\Delta_{peak} = 2\%$. Three exemplary fibers have zero dispersion wavelengths of 1524nm, 1533nm and 1536nm. Such fibers can have a dispersion slope of 0.043 ps/nm^2-km, and the loss at 1550nm can be approximately 0.6dB/km. The nonlinear coefficient can be $\gamma = 9\ W^{-1}km^{-1}$, or a factor of 4.5x higher than in DSF. The enhancement can be attributed to two factors: a smaller effective area and a higher germanium content. The effective area can be reduced to about $A_{eff} = 16.5\ \mu m^2$, or about a factor of 3.3 less than in DSF. Also, the nonlinear index of refraction is about 1.35x larger than in DSF due to the extra germanium used to increase Δ_{peak} from 1% in DSF to 2% for the high nonlinearity fiber. In addition the mode field diameter at 1550nm can be measured to be 4.67 μm.

For the gain fiber used in the Raman amplifier, a figure-of-merit for the fiber can be defined in some embodiments. A figure-of-merit that can be measured and indicate amplifier performance is the ratio of the Raman gain coefficient to the loss at the signal wavelength. The higher this figure-of-merit, the better the performance of

the amplifier. This figure-of-merit for different fibers in some embodiments is provided in Table 1. In one embodiment the lowest figure-of-merit is found for standard (non-dispersion-shifted) SMF-28 fiber. This fiber can have a low germanium content and a relatively large $A_{eff} = 86\ \mu m^2$. The figures-of-merit for the high-nonlinearity (Hi-NL) fiber can exceed the other fibers, with a value about two-fold larger than Lucent True-wave fiber in one example. Although the DCF's can have a relatively large figure-of-merit for Raman amplification, they can have very large dispersion coefficients for S-band signals.

Table 1. Comparison of Raman gain figure-of-merit for different fibers measured.

Fiber Type	**Gain [dB/W-km] @ 1500nm**	**Loss [dB/km] @1500nm**	**Figure-of-Merit**
Corning SMF-28	2.2	0.19	11.6
Lucent True-Wave	3.3	0.21	15.7
Corning SMF-DS	4.0	0.2	20.0
Corning DCF	11.75	0.445	26.4
Lucent DCF	13.72	0.5	27.6
Hi-NL	18.0	0.6	30.0

One embodiment with Hi-NL fiber has significant improvements in terms of fiber length and pump power used in a Raman amplifier. One embodiment has an amplifier made out of Lucent True-Wave fiber. The specifications for the unit can be: low dispersion around 1520nm, 15dB of peak gain, electrical and optical NF under 6dB, and multi-path interference (MPI) under 50dB. A two-stage design for the Raman amplifier can be used, as illustrated in Figure 14. In particular, 6km of True-Wave fiber can be used in the first stage and 10-12km of fiber can be used in the second stage. The measured performance of the amplifier can be: peak gain of 15.2dB at 1516nm, 3dB bandwidth of 26nm (between 1503-1529nm), and electrical and optical noise figure under 6dB. For example, the gain versus wavelength and noise figure versus wavelength for the unit is illustrated in Figures 15 and 16. This performance can have a pump power of about 1.0 W at 1421nm.

In one embodiment, the True-Wave fiber in this design is replaced with Hi-NL fiber. Reductions in fiber lengths and pump power requirements can be achieved. The Hi-NL fiber can meet the dispersion requirement in some embodiments. The DCF fibers can lead to the introduction of large amounts of dispersion. Referring to the Table 1 comparison, the fiber lengths can be chosen to keep roughly the same amount of net loss. In one embodiment, fiber lengths can be roughly 2km for the first stage and 3.3-4km for the second stage. Pump power requirements can be lowered by the ratio of figures-of-merit, or roughly to 0.5W. In various embodiments, this power range can be provided by the Raman oscillator, or by polarization and wavelength multiplexing 3-4 LD's together. Hi-NL fiber can reduce the size of the amplifier as well as permit LD pumping in some embodiments.

The fiber can have single-mode operation for the pump as well as the signal wavelengths in some embodiments. Cut-off wavelength λ_c of the fiber can be shorter than any of the pump wavelengths in some embodiments. The pump can be multi-mode, and noise can be introduced from the beating between modes in other embodiments.

Various embodiments have reduction of the Raman amplifier size and pump requirements while maintaining low net dispersion at the operating wavelengths, and include one or more of:

(A) A Raman amplifier using a gain fiber characterized in that

- nonlinear coefficient $\gamma > 3\ W^{-1}km^{-1}$
- zero dispersion wavelength in the range of $1300 < \lambda_o < 1800$nm, depending more precisely on the specifications
- Loss over the operating wavelength of < 2dB/km, with a preference for loss < 1dB/km

(B) A Raman amplifier using a dispersion managed gain fiber characterized in that

- nonlinear coefficient $\gamma > 3\ W^{-1}km^{-1}$
- dispersion management done using segments of fiber with zero dispersion wavelength in the range of $1300 < \lambda_o < 1800$nm, depending more precisely on the specifications. Given an operating band, certain fiber segments have λ_o less than the operating band and other fiber segments have λ_o greater than the operating

band. The local dispersion can be kept high, while the path average dispersion can be close to zero in the signal band.

➢ Loss over the operating wavelength of certainly < 2dB/km, with a preference for loss < 1dB/km

(C) Fibers as in (A) or (B) with cut-off wavelength shorter than any of the pump wavelengths.

(D) A Raman amplifier as described in (A) that is pumped by LD's. For two or more LD's, the power can be combined by using polarization and wavelength multiplexing using polarization beam combiners and wavelength-division-multiplexers.

(E) A Raman amplifier as in (B) that is pumped by LD's. For two or more LD's, the power can be combined by using polarization and wavelength multiplexing using polarization beam combiners and wavelength-division-multiplexers.

(F) At least a two-stage Raman amplifier that uses the improvements in (A),(B),(C),(D) or (E).

(G) Other factors as above with different numerical ranges

Some embodiments include standard dispersion fiber, i.e., fibers with zero dispersion wavelength around 1310nm. The zero dispersion wavelength can fall in the S- or S^+-bands in some embodiments. For example, this is true for so-called non-zero-dispersion-shifted fiber (NZ-DSF). In these fibers, it can be difficult to run multi-wavelength WDM channels due to cross-talk from four-wave mixing. Four-wave-mixing can require phase matching, and the phase matching can be easier to satisfy in the neighborhood of the zero dispersion wavelength. One embodiment is a broadband fiber transmission system with non-zero dispersion fiber that has zero dispersion wavelengths less than 1540 nm or greater than 1560 nm that uses optical amplifiers to compensate for loss.

WDM can maximize capacity in any given band in some embodiments. Hybrid amplifiers can be useful in the vicinity of the zero dispersion wavelength in some embodiments. NZ-DSF fibers can have a zero dispersion wavelength either < 1540nm or >1560nm in some embodiments. For operation near the zero dispersion wavelength, e.g., $|\lambda - \lambda_o| < 25$nm, the four-wave-mixing penalty can be avoided by

using hybrid optical amplifiers in one embodiment. Since the effective NF of hybrid amplifiers can be lower than for discrete amplifiers, the power levels for the signals can be reduced to the point that four-wave-mixing can no longer be a limitation, in another embodiment.

One embodiment of a broadband fiber transmission system comprises a transmission line and one or more semiconductor lasers. The transmission line can have at least one zero dispersion wavelength λ_o. The transmission line can transmit an optical signal of λ. The optical signal can have a wavelength λ in the range of 1430 nm and 1530 nm, or in the range of 1530 nm and 1630 nm. The signal wavelength at λ can be sufficiently low in power to avoid at least one fiber non-linearity effect. The at least one fiber non-linearity effect can comprise four-wave mixing, and/or modulation instability. λ can be close to λ_0. λ can be within 20 nm, or within 30 nm λ_0. λ_0 can be less than 1540 nm, and/or greater than 1560 nm. The transmission line can include a distributed Raman amplifier. The distributed Raman amplifier can amplify the optical signal through Raman gain. The distributed Raman amplifier can have sufficient gain to compensate for losses in the transmission line. The one or more semiconductor lasers can operate at wavelengths λ_p for generating a pump light to pump the Raman amplifier.

One embodiment of a broadband fiber transmission system comprises a transmission line and one or more semiconductor lasers. The transmission line can have at least one zero dispersion wavelength λ_o. The transmission line can transmit an optical signal of λ. The optical signal can have a wavelength λ in the range of 1430 nm and 1530 nm, or in the range of 1530 nm and 1630 nm. The signal wavelength at λ can be sufficiently low in power to avoid at least one fiber non-linearity effect, such as four-wave mixing, and/or modulation instability. The transmission line can include a distributed Raman amplifier. The transmission line can include a discrete optical amplifier. The amplifiers can have sufficient gain to compensate for losses in the transmission line. The discrete optical amplifier can amplify the optical signal of λ. The discrete optical amplifier can be a rare earth doped amplifier, an erbium doped fiber amplifier, a Raman amplifier, and/or a thulium doped fiber amplifier. The one or more semiconductor lasers can operate at wavelengths λ_p for generating a pump light to pump the amplifiers. λ can be close to

λ_o. λ can be within 30 nm, or within 20 nm, of λ_o. λ_o can be less than 1540 nm, and/or greater than 1560 nm.

One embodiment of a method of broadband amplification comprises providing a broadband fiber transmission system with a transmission line having at least one zero dispersion wavelength λ_o, the transmission line including a distributed Raman amplifier that amplifies an optical signal through Raman gain; transmitting an optical signal of λ; pumping the Raman amplifier with pump light λ_p, wherein λ is close to λ_o and λ_o is less than 1540 nm or greater than 1560 nm. λ can be within 30 nm, or within 20 nm, of λ_o. The optical signal can have a wavelength λ in the range of 1430 nm and 1530 nm, or in the range of 1530 nm and 1630 nm. The signal wavelength at λ can be sufficiently low in power to avoid at least one fiber non-linearity effect, such as four-wave mixing, and/or modulation instability. The distributed Raman amplifier can have sufficient gain to compensate for losses in the transmission line.

One embodiment of a method of broadband amplification comprises providing a broadband fiber transmission system with a transmission line having at least one zero dispersion wavelength λ_o, the transmission line including a distributed Raman amplifier and a discrete optical amplifier that amplify an optical signal of λ; transmitting an optical signal of λ; pumping the Raman amplifier and discrete optical amplifiers with pump light λ_p, wherein λ is close to λ_o and λ_o is less than 1540 nm or greater than 1560 nm. λ can be within 30 nm, or within 20 nm, of λ_o. The optical signal can have a wavelength λ in the range of 1430 nm and 1530 nm, or in the range of 1530 nm and 1630 nm. The discrete optical amplifier can be a rare earth doped amplifier, an erbium doped fiber amplifier, a Raman amplifier, and/or a thulium doped fiber amplifier. The signal wavelength at λ can be sufficiently low in power to avoid at least one fiber non-linearity effect, such as four-wave mixing, and/or modulation instability. The amplifiers can have sufficient gain to compensate for losses in the transmission line.

Various other modifications can be readily apparent to those skilled in the art without departing from the scope and spirit of the invention. Accordingly, it is not intended that the scope of the claims appended hereto be limited to the description set forth herein, but rather that the claims be construed as encompassing all the features of the patentable novelty that reside in the present invention, including all features that

would be treated as equivalents thereof by those skilled in the art to which this invention pertains.